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Simulation for signature of Higgs boson in UHE cosmic ray interactions through vacuum excitation

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Abstract : We present here a new approach for signature of Higgs boson production in ultra high energy cosmic ray (UHECR) interactions using the thermofield theory The idea is the decay of Higgs bosons that are produced through bubble formation due to vacuum excitation in an UHECR collision with air nuclei. We develop a model of hadronic interaction based on the GENCL code of the UA5 experiment of CERN and CORSIKA code (Karlsruhe report), incorporating a fraction of energy transfer to bubble formation by phase transition due to vacuum excitation and subsequent multiparticle production *via* conversion of Higgs boson to heavy fermion pairs Such events are expected to have high multiplicity and excess muons We compare the muon multiplicity distribution with and without this effect for different fractions of energy transfer to vacuum It has been found that the Higgs boson production mechanism has significant effect starting from $E_p \sim 10^{18}$eV

Keywords UHE cosmic ray interaction, Monte-Carlo simulation, Higgs boson production, hadronic interaction, vacuum excitation, bubble formation.

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1. Introduction

The Higgs boson is the key missing ingredient of the Standard Model (SM) and is responsible for spontaneous breaking of $SU(2)_L \times U(1)_Y$ symmetry of electroweak interactions. The quest for its existence is one of the urgent endeavours of the on-going and future particle physics experiment. So far, direct experimental searches for this scalar proved fruitless. The discovery of this particle is expected in the Large Hadron Collider (LHC) of CERN, with experimental detection techniques guided by theoretical expectations. In this article, we explore the idea of possible detection of Higgs signature in ultra high energy cosmic ray (UHECR) interactions with air nuclei. In UHECR interactions, there is possibility that the vacuum becomes locally hot, bubbles are formed by phase transition, Higgs bosons are produced and decay very fast to heavy fermion pairs. This effect is manifested in a very rapid increase of the multiplicity of charged hadrons with energy. The possibility of vacuum excitation depends on the fraction of the total energy of the collision (centre of mass energy) that goes to local vacuum excitation and bubble formation. This fraction of energy is not known.

By considering a nonperturbative mechanism of thermofield theory, Mishra *et al* [1] have claimed that the Higgs particles are produced through vacuum excitations. This fact has been included in our present simulation model, which is based on the theoretical formalism of vacuum excitation using thermofield theory [2] followed by Higgs boson production and decay to high energy muons. The high energy muons produced at very first collision, bear signature of Higgs boson production. We therefore, incorporate this effect in the conventional hadronic cascade simulation program based on the GENCL code of UA5 experiment [3] of CERN and CORSIKA [4] code of Karlsruhe. This is our modified form of earlier mechanism [5] for multiparticle production in the simulation of a cosmic ray cascade in the atmosphere due to UHE interactions. The theoretical basis of our model is described in Section 2. Section 3 is devoted to explain the structure of our model and Monte-Carlo algorithm to simulate the hadronic cascade. In the present analysis, we try to emphasize only on the concept of Higgs production by the new mechanism and for the sake of simplicity, we consider only first nuclear interaction. The interaction and decay processes in the atmosphere are simulated only for hadrons (π, k, and N) and muons above 0.3 GeV, 1 GeV, 3 GeV, 10 GeV and 30 GeV. For the

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production and decay processes of the hadrons and Higgs boson, subroutines are developed and are coupled to the cascade program in order to generate muons, to which most of the hadrons and Higgs particles finally decay. The results of the simulation are discussed in Section 4.

2. Higgs boson production through vacuum excitation

2.1. *Temperature dependence of vacuum :*

Using the methodology of thermofield dynamics [2], we consider the basic idea of the temperature dependence of vacuum. In general, in the nonperturbative methodology of field theory, the coherent state of vacuum at zero temperature is defined as [1]

$$|vac'\rangle \equiv U|vac\rangle, \tag{1}$$

where U is a unitary operator. For complex field ϕ, the vacuum expectation value (VEV) is given as

$$\langle vac'|\phi(z)|vac'\rangle = \frac{\xi}{2}. \tag{2}$$

The expectation value of the Hamiltonian density is given by

$$\varepsilon_0 = \langle vac'|\tau^{00}|vac'\rangle = -\frac{1}{2}m^2\xi^2 + \left(\frac{\lambda}{4}\right)\xi^4. \tag{3}$$

A minimization of energy density ξ_0 with respect to ξ gives the result $\xi = \xi_0 = \left[m^2/\lambda\right]^{1/2}$. This concept can be generalized to finite temperature by using the methodology of thermofield dynamics [2]. The temperature dependent vacuum is given by

$$|vac', \beta\rangle = U(\beta)|vac'\rangle, \tag{4}$$

where $\beta = 1/kT$. If τ^{00}_{eff} is effective Hamiltonian density, then energy density at temperature β becomes

$$\begin{aligned} V(\xi, \beta) &\equiv \varepsilon(\beta) = \langle vac', \beta|\tau^{00}_{eff}|vac', \beta\rangle \\ &= \frac{1}{2}(2\pi)^{-3}\int \frac{\omega(k,\beta)^2 + k^2 + 3\lambda\xi^2 - m^2}{\omega(k,\beta)\left\{\exp\left[\beta\omega(k,\beta)\right] - 1\right\}}dk \\ &+ \frac{3\lambda}{4}\left[(2\pi)^{-3}\int \frac{1}{\omega(k,\beta)\left\{\exp\left[\beta\omega(k,\beta)\right] - 1\right\}}dk\right]^2 \\ &+ \frac{\lambda}{4}\xi^4 - \frac{m^2}{2}\xi^2, \end{aligned} \tag{5}$$

where $\omega(k,\beta) = \left[k^2 + m_H(\beta)^2\right]^{1/2}$, with $m_H(\beta)$ being the Higgs boson mass at temperature $1/\beta$.

For numerical evaluation it is useful to rewrite eq. (5) in terms of the dimensionless quantities with substitutions:

$$z = \frac{\xi}{\xi_0},\ \mu = \frac{m_H(\beta)}{\xi_0},\ y = \beta\xi_0,\ x = \frac{k}{\xi_0},$$

where ξ_0 is the value of $\xi_{min} = \left(m_H^2/\lambda\right)^{1/2}$ for zero temperature The expression for effective potential becomes

$$\begin{aligned} V(z,y) &= \xi_0^4\left[\frac{\lambda}{4}z^4 - \frac{\lambda}{2}z^2 + \frac{1}{2}I_1(z,y) + \frac{3\lambda}{4}\left[I_2(z,y)\right]^2\right] \\ &\equiv \xi_0^4 V_1(z,y), \end{aligned} \tag{6}$$

where

$$I_1(z,y) = \frac{1}{2\pi^2}\int_0^\infty \frac{x^2\left[\omega(x)^2 + x^2 + \lambda\left(3z^2 - 1\right)\right]}{\omega(x)\left\{\exp\left[y\omega(x)\right] - 1\right\}}dx \tag{7}$$

and

$$I_2(z,y) = \frac{1}{2\pi^2}\int_0^\infty \frac{}{\omega(x)\left\{\exp\left[y\omega(x)\right] - 1\right\}}dx, \tag{8}$$

with $\omega(x) = \left(x^2 + \mu^2\right)^{1/2}$. The gap in energy density of the thermal vacuum with respect to the vacuum at zero temperature is given by

$$\Delta\varepsilon(\beta) = V(\xi_{min}, \beta) - V(\xi_{min}, \beta = \infty) = \xi_0^4\left[V_1(z_{min}, y) + \frac{\lambda}{4}\right]. \tag{9}$$

2.2. *Vacuum excitation and bubble formation:*

The possible local heating of vacuum with particle collision and dynamics of vacuum excitation and bubble formation is theoretically studied by Mishra *et al* [1] considering the nonperturbative mechanism for the production of Higgs boson With vacuum as the medium in which collision takes place, a local destabilization of it can occur if enough energy is pumped into a microscopic volume which thermalizes locally and forms bubble having a nonzero temperature and local thermal equilibrium. The total energy of such a locally excited region or bubble can be given as

$$E_b = \int \Delta\varepsilon\left[\beta(r)\right]dr, \tag{10}$$

where $\Delta\varepsilon\left[\beta(r)\right]$ is the gap in energy density of the thermal vacuum with respect to the vacuum at zero temperature, given by

$$\Delta\varepsilon\left[\beta(r)\right] = \xi_0^4\left[V_1\left(z_{min}, y(r)\right) + \frac{\lambda}{4}\right], \tag{11}$$

with $\varepsilon_0 = \left(m_H^2/\lambda\right)^{1/2}$ being the field expectation value corresponding to the minimum potential $V_1\left(z_{min}, y(r)\right)$ as given in eq. (6). V_1 and $\beta = 1/kT$ are now spatially dependent. The number of Higgs boson inside the bubble is given by

$$n_H = \int N[\beta(r)]\,dr, \tag{12}$$

where $N(\beta)$ is the number density of the Higgs particle at temperature β and is given by

$$N(\beta) = (2\pi)^{-3} \int \frac{1}{\exp[\beta\omega(k,\beta)] - 1}\,dk, \tag{13}$$

with $\omega(k,\beta) = \left(k^2 + m_H^2\right)^{1/2}$, m_H being the Higgs boson mass. The temperature distribution inside the bubble is taken as

$$\beta(r)^{-1} = T(r) = T_0 \exp(-ar^2), \tag{14}$$

where T_0 is the temperature at the centre of the bubble and the parameter a decides the region over which the vacuum is excited, with bubble volume approximately $a^{-3/2}$.

3. The model

3.1. *The structure:*

Considering the nonperturbative methodology of thermofield theory, we develop a model of hadronic interaction in the light of possibility of Higgs boson production through vacuum excitation due to fraction of energy transfer to the vacuum during UHECR interactions. Fraction of centre of mass energy $\left(\sqrt{s}\right)$ that goes to bubble is unknown [1]. For definiteness, we consider various fraction of $\sqrt{s}$ that goes to bubble formation as $f_e = 0.0$, 0.01, 0.02, 0.5.

The gap in energy density of thermal vacuum with respect to the vacuum at zero temperature β and number density of Higgs boson at different temperature is calculated using eqs. (11) and (13) for the simulated mass of Higgs boson for different central temperatures T_0. Assuming a given primary energy of proton ($E_p = 10^{15} - 10^{19}$ eV) and a given fraction ($f_e = 0.0 - 0.5$) of the energy transfer for vacuum excitation and bubble formation, first, bubble energy $E_b\left(= \sqrt{s}.f_e\right)$ is calculated for each event. Then the volume of the bubble or the excited region for each event is calculated $\left(E_b/\Delta\varepsilon\right)$. Finally, the mean number of Higgs boson is evaluated for corresponding bubble volume. We parametrize approximately the relation between average number of Higgs bosons $< N_H >$ with bubble energy E_b. We have used these equations in our simulation program to calculate average number of Higgs boson for a particular event and primary energy of proton. The actual number (N_H) for a particular event and primary energy is chosen from a Poisson distribution with this mean.

In the energy range $\sqrt{s} \sim 350 - 500$ GeV, the linear Collider (LC) has provided that Higgs boson mass to be lies in the range $m_H = 200$ GeV. The dominant production mechanism for such a light Higgs boson is $e^+e^- \to hZ$, with the largest decay channel being $h \to b\bar{b}$ or $h \to WW*$ [6, 7]. Indirect evidence from precision measurements at e^+e^- colliders suggest the existence of a light Higgs boson in the mass range of 95 – 235 GeV at 95% confidence level with a statistical preference towards the lower end [8]. Direct experimental searches at the CERN Large Electron Positron Collider (LEP) place the mass of a SM like Higgs state, with a significant decay branching ratio into bottom (b) quarks, approximately above 115 GeV. An alternative analysis based only on the assumption of Higgs boson, decay into hadronic jets, without b-tagging leads to a bound of about 113 GeV [7]. Following all these arguments for Higgs boson mass, we have used the following decay channels of the Higgs boson for our model to develop subroutines which are incorporated with the main cascade program to illustrate the idea of Higgs production through vacuum excitation [5, 9]:

(i) $m_H < m_w$, $H \to b\bar{b}(\sim 90\%)$, $\tau^+\tau^-(\sim 10\%)$,

(ii) $m_w < m_H < m_z$, $H \to b\bar{b}(\sim 85\%)$, $\tau^+\tau^-(\sim 10\%)$, $c\bar{c}(\sim 4\%)$,

(iii) $m_z < m_H < 2m_w$, $H \to b\bar{b}(\sim 80\% - 1\%)$, $WW*(\sim 0.01\% - 97\%)$, $ZZ*(\sim 0\% - 10\%)$,

(iv) $2m_w < m_H < 2m_z$, $H \to WW(\sim 94\% - 100\%)$,

(v) $m_H > 2m_z$, $H \to WW(\sim 75\%)$, $ZZ(\sim 25\%)$.

The *WW* and *ZZ* channels further decay to electrons, muons and neutrinos according to $W \to e\nu$, $\mu\nu$ or $Z \to e^+e^-$, $\mu^+\mu^-$. $b\bar{b}$ channel either directly decays to muons or electrons (10%) or indirectly *via* intermediate states $\tau^+\tau^-, \pi^+\pi^-, 2\pi_0$, *etc.* $c\bar{c}$ channel also either directly decay to muons or electrons (~ 6%) or indirectly *via* various intermediate states [10]. The $\tau^+\tau^-$ decay modes are decided by individual channels:

$$\tau^{\pm} \to \mu^{\pm}\nu\bar{\nu}(\sim 18\%),\ e^{\pm}\nu\bar{\nu}(\sim 17\%),\ h^{\pm}\nu\bar{\nu}(\sim 52\%).$$

We have calculated the muon multiplicity by considering only the various decay channels leading to muons. In the hadron-air interaction model, the particles are produced in clusters according to recent theoretical [11] and experimental [3] considerations. In our present simulation for ultra high energy cosmic ray interactions, we consider only non-diffractive (ND) events (actually non-single diffractive), where particle produced in a central region, flat in rapidity, and in two fragmentation regions. Here, an event is built up of two leading and a varying number of central clusters. Each cluster is given a transverse momentum P_T and rapidity y. After transforming the rapidities to conserve energy and momentum, the clusters are made to decay isotropically.

3.2. Monte-Carlo algorithm :

The Monte-Carlo simulation program is written following the algorithm of the GENCL code developed at CERN, by the UA5 collaboration, including the effect of nuclear target mass, as follows:

(i) The number of charged hadrons n_{ch} is chosen from a negative-binomial (NB) distribution:

$$P(n_{ch}) = \quad n_{ch}+k-1 \quad \frac{\langle n_{ch}\rangle/k}{1+\langle n_{ch}\rangle/k} \quad \frac{1}{1+\langle n_{ch}\rangle/k} \tag{15}$$

with the following parameters :

$$\langle n_{ch}\rangle = -7.0 + 7.25 s^{0.127}, \tag{16}$$

and

$$k^{-1} = -0.104 + 0.058 \ln\left(\sqrt{s}\right), \tag{17}$$

where s is in GeV^2.

(ii) Cluster formation and decay is the basic multiparticle production mechanism. Out of six different clusters, we consider only three, *viz.* pion, kaon and the leading cluster, excluding the less frequent nucleon, hyperon and Xi pairs. The nature of the leading particles (p or n) is chosen considering the charge exchange probability as given in [3].

(iii) Number of kaons produced is grouped into pairs (cluster) of zero strangeness including neutral kaon and kaon resonances pairs [3, 12]. All pairs have same production probability and each kaon is a k^* with 60% probability, according to CERN intersecting storage rings (ISR) measurements [13]. The actual number of kaon clusters is drawn from a Poisson distribution with a mean deduced from the k/π ratio,

$$R_k = \langle k^{\pm}\rangle / \langle \pi^{+}\rangle = 0.024 + 0.0062 \ln(s). \tag{18}$$

The k^*'s decay into $k\pi$ pairs as follows:

$$k^{*0} \rightarrow k^0\pi^0\left(\frac{1}{3}\right), k^+\pi^-\left(\frac{2}{3}\right), \tag{19}$$

$$k^{*+} \rightarrow k^0\pi^+\left(\frac{1}{3}\right); k^+\pi^0\left(\frac{2}{3}\right), \tag{20}$$

k^0 's (and $\bar{k}^0$'s) are considered to be k_S^0 or k_L^0 with equal probability. All k^0's, $k^{\pm}$ and pions finally decay to muons and electrons and their decay are governed by standard branching ratio.

(iv) Remaining charged particles are π^+ and π^-, which are grouped into clusters including π^0's. The algorithm is based on drawing the number of charged pions from a Poisson distribution with an average of 1.8, repeatedly until there are no charged particle left and then drawing π^0's from an independent Poisson distribution with the following parameter [3]

$$\mu_{\pi^0} = \left[0.5(2 + 1.03 n_{ch}) - 0.4\mu_k\right]/n_c, \tag{21}$$

where $\mu_k = \left[R_k/(1+R_k)\right] n_{chl}$, n_{chl} being the number of charged particles left to be simulated, and n_c is the number of pion clusters.

(v) All clusters made up of more than one particle are given some excitation energy in terms of an additional mass. For the kaon clusters, the excitation energy follows the distribution

$$\frac{dn}{dE^2} : \exp \quad -2E \tag{22}$$

where b is a free parameter having the value 0.75 GeV for kaon clusters. The pion clusters are given masses m from the following distribution

$$\frac{dN}{dm} = 1.1\left[1 + N_0(0, 0.2)\right] \exp\left[\left(\frac{1}{3}\right) n_\pi - 1\right], \tag{23}$$

where n_π is the number of pions in the cluster and N_0 (0, 0.2) is a number drawn from a Gaussian distribution with mean 0 and standard deviation 0.2 GeV.

(vi) Transverse momenta P_T and longitudinal momenta P_l are given to the clusters in two steps. The transverse momenta are randomized from either an exponential distribution

$$\frac{dN}{dP_T^2} \propto \exp(-bP_T), \tag{24}$$

or from an inverse power-law distribution

$$\frac{dN}{dP_T^2} \quad (P_T + P_0)^{\alpha} \tag{25}$$

where $b = 6$ GeV/c, $P_0 = 3$ GeV/c, $\alpha = 3 + 1/[0.01 + 0.011 \ln(s)]$. For the single pions (~10% of all clusters), P_T is always sampled from the exponential distribution. In other cases, the relative amount of the two distributions is made to depend on the multiplicity of the event. For proton-air interactions, these distributions are multiplied by the parameter

$$R(P_T) = 0.0363\, P_T + 0.057 \text{ for } P_T \leq 4.52 \text{ GeV}/c. \tag{26}$$

The azimuthal angles of the leading nucleons and of the mesons clusters are chosen randomly between 0 and 2π. To conserve momenta in the XY-plane perpendicular to the beam axis (Z-direction), we make two independent linear translations in the components of

$$P_i^{new} = P_i^{old} - \left(\sum P_i^{old}\right)/N, \; i = x, y, \tag{27}$$

where the summation is over the N clusters in the event. Here, P_T is generated independent of rapidity. Longitudinal momentum is given to a cluster by assigning to it rapidity y,

$$P_L = m_T \sinh(y), \tag{28}$$

where $m_T = \sqrt{\left(m^2 + P_T^2\right)}$ is the transverse mass. Rapidity distribution has a central plateau and a fall-off at higher values of $|y|$, and can be described analytically by two Gaussian peaks [14], with the following parameters [15]:

$$s_1 = 0.146 \ln(E_p) + 0.164, \tag{29}$$

and

$$\sigma_1 = 0.120 \ln(E_p) + 0.255. \tag{30}$$

Box-Muller method is used to generate the rapidities and the two leading clusters are given the highest and lowest rapidities. They are converted to longitudinal momenta P_L and so adjusted as to conserve total momentum and energy, after assigning a fraction $\langle k \rangle$ (inelasticity parameter ~ 0.5) of available energy to leading nucleons.

(vii) Each cluster with given energy is made to decay *via* the available channels with a probability proportional to their respective branching ratios. The numbers of muons above threshold energy $\left(E_\mu^{thr}\right)$ 0.3 GeV, 1 GeV, 3 GeV, 10 GeV and 30 GeV are counted for each event.

4. Results and discussion

We have presented a simple model for Higgs boson production in UHECR interactions and the Monte-Carlo simulation program based on this model following the algorithm of the GENCL code developed at CERN, by UA5 collaboration [3] and using some features of the CORSIKA code of Karlsruhe [4]. Here, we have basically tried to manifest the idea of new mechanism of Higgs particle production in UHECR interactions due to vacuum excitation. For the sake of simplicity, we have prepared our simulation program for first interaction only. We run this program for primary energies $E_p = 10^{15} - 10^{19}$ eV and different fractions of energy transfer to bubble formation f_e (0.0 – 0.5). The resulting muon multiplicity distribution for 1000 showers for different E_p and f_e are compared with corresponding simulations with $f_e = 0$. In order to derive signature of Higgs boson production, muon multiplicity distribution for muon energy thresholds of 0.3 GeV, 1 GeV, 3 GeV, 10 GeV and 30 GeV are selected as the probe. Results are summarized in Figures 1-7. It is seen that the Higgs

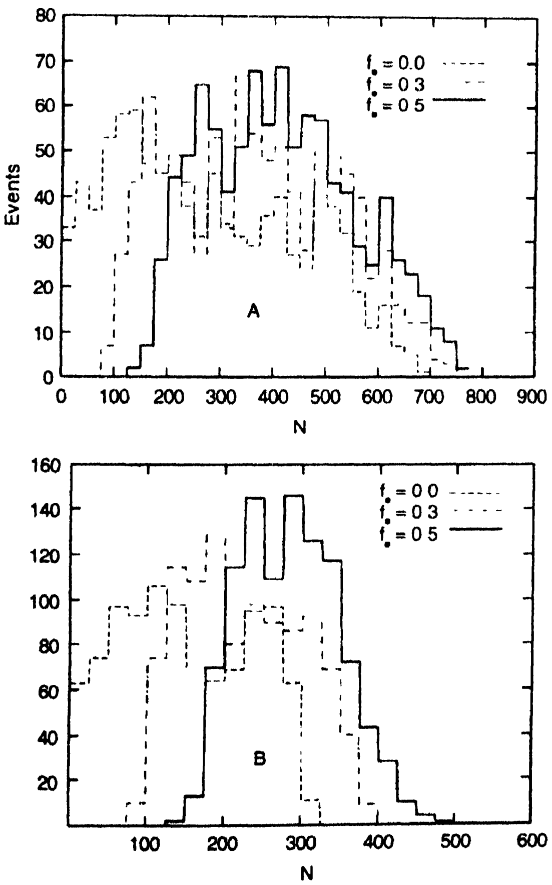

Figure 1. Muon multiplicity distribution at first interaction level for 1000 showers with primary energy of 10^{18} eV for different fraction of energy transfer. 'A' represents 0.3 GeV and 'B' represents 30 GeV muon threshold energies.

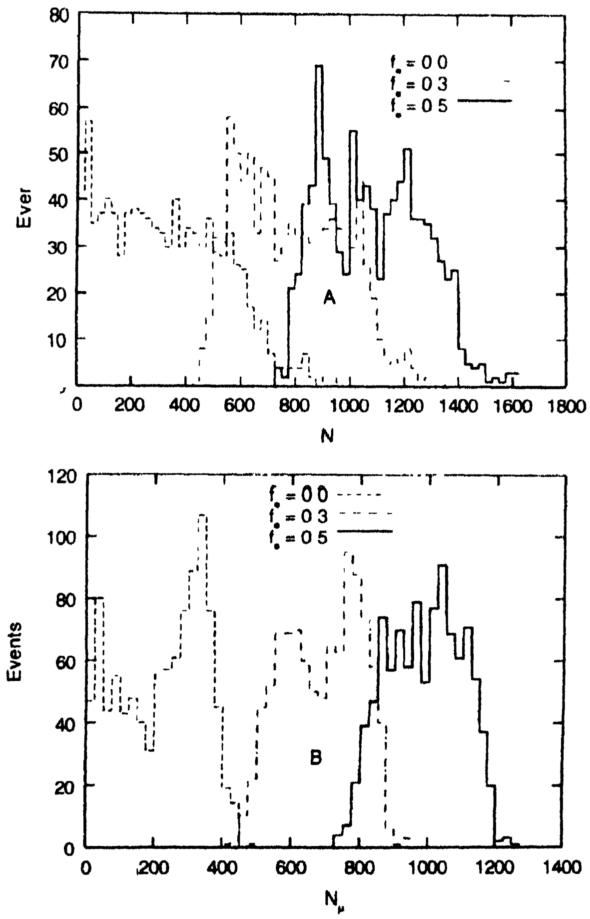

Figure 2. Muon multiplicity distribution at first interaction level for 1000 showers with primary energy of 10^{19} eV for different fraction of energy transfer. 'A' represents 0.3 GeV and 'B' represents 30 GeV muon threshold energies.